

# Light Emitting Diode Taxiway Edge Lights Emissions Evaluation

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16. Abstract <p>This study was conducted to evaluate taxiway edge fixtures using light emitting diode (LED) technology to determine (1) if electrical emission levels from these fixtures are sufficient to cause interference to airfield circuits and warrant further investigation and (2) if there is a need to change the certification requirements for these electrical emissions.</p> <p>Five LED fixtures from different manufacturers were tested. The airfield lighting test bed located at the William J. Hughes Technical Center was used to measure the emissions of the fixtures.</p> <p>Electrical emissions occur in two forms, harmonic and nonharmonic. Harmonics are a distortion of the normal electrical frequencies emitted by the LED fixtures, which can cause problems with other equipment. Multiple electronic devices on a circuit, all emitting similar harmonics, can be additive and disruptive to the power distribution network. Harmonic emissions can cause voltage variations and overheating of the airfield circuit wiring. Nonharmonic emissions are a result of the circuitry in the power supply, which causes frequencies that are multiples of the power supply switching frequency. This can cause interference on the electrical circuit. The current certification requirements contain procedures to test for emissions, with the lowest frequency being 150 kHz.</p> <p>The data from this study showed that four out of five fixtures had significant emissions that could possibly cause interference. These emissions were at a frequency as low as 12 kHz, which is much lower than the current certification requirements of 150 kHz, and warrants a change in the certification requirements.</p>					
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## LIST OF ACRONYMS

ac	Alternating current
A-SMGCS	Advanced Surface Movement Guidance and Control System
CCR	Constant current regulator
CENELEC	European Committee for Electrotechnical Standardization
CISPR	International Special Committee on Radio Interference
dB	Decibel
dB $\mu$ A	Decibel microamps
dB A	Decibel amps
dBmA	Decibel milliamps
dc	Direct current
EUT	Equipment under test
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
IEC	International Electrotechnical Commission
LED	Light emitting diode
LISN	Line impedance stabilization network
PC	Personal computer
R&D	Research and development
RGL	Runway guard lights
THD	Total harmonic distortion

## EXECUTIVE SUMMARY

This study was conducted to evaluate taxiway edge fixtures using light emitting diode (LED) technology to determine (1) if electrical emission levels from these fixtures are sufficient to cause interference to airfield circuits and warrant further investigation and (2) if there is a need to change the certification requirements for these electrical emissions.

Five LED fixtures from different manufacturers were tested. The airfield lighting test bed located at the William J. Hughes Technical Center was used to measure the emissions of the fixtures.

Electrical emissions occur in two forms, harmonic and nonharmonic. Harmonics are a distortion of the normal electrical frequencies emitted by the LED fixtures, which can cause problems with other equipment. Multiple electronic devices on a circuit, all emitting similar harmonics, can be additive and disruptive to the power distribution network. Harmonic emissions can cause voltage variations and overheating of the airfield circuit wiring. Nonharmonic emissions are a result of the circuitry in the power supply, which causes frequencies that are multiples of the power supply switching frequency. This can cause interference on the electrical circuit. The current certification requirements contain procedures to test for emissions, with the lowest frequency being 150 kHz.

The data from this study showed that four out of five fixtures had significant emissions that could possibly cause interference. These emissions were at a frequency as low as 12 kHz, which is much lower than the current certification requirements of 150 kHz, and warrants a change in the certification requirements.

## INTRODUCTION

The Airport Technology Research and Development (R&D) Branch in response to a request from the Office of Airport Engineering Division undertook this project to evaluate the effects on existing lighting circuits caused by the use of light emitting diode (LED) technology for airport taxiway edge lighting. This research will assist in the revision of advisory circulars (AC) concerning airport taxiway edge lights.

### OBJECTIVE.

This effort evaluated LED taxiway edge lights to determine (1) if emission levels are sufficient to cause interference to airfield circuits and warrant further investigation and (2) if there is a need to change the requirements for these emissions. The evaluation looked for harmonic distortion and nonharmonic emissions on five LED taxiway edge lights.

### RELATED DOCUMENTS.

Related documents dealing with this evaluation project are:

- Federal Aviation Administration (FAA) Advisory Circular 150/5340-24, "Runway and Taxiway Edge Lighting System," September 3, 1975.
- FAA Advisory Circular 150/5345-46B, "Runway and Taxiway Light Fixtures," September 1, 1998.
- FAA LED Engineering Brief, Light Sources Other Than Incandescent and Xenon for Airport and Obstruction Lighting Fixtures, Alvin Logan, AAS-100, March 2004.

## BACKGROUND

LED-based airfield lighting fixtures are being installed on an increasing number of airfields. Initially, these fixtures were limited to obstruction lighting, which used some colors that were more readily produced by LED components. Also, with obstruction lights, the size of the package and the number of LEDs were not critical. The next, logical place to implement LEDs was for taxiway edge lights. This came as a result of the blue LED becoming a practical component.

In the last 10 or so years, with the increased number of airports going to low visibility operations (Advanced Surface Movement Guidance and Control System (A-SMGCS)) or simply adding runway guard lights (RGL) to improve awareness of runway entrances, the use of addressable devices has been increasing since a high percentage of in-pavement RGLs use some form of addressable device. These devices use communications on the series circuit to synchronize the flashing of the lights in a hold bar, and also use communications on the circuit to collect status of the fixtures to ensure the operational state is known.

Looking at the emissions requirements, the only standard in place is Federal Communications Commission (FCC) Part 15. As will be discussed below, Part 15 does not deal with the

characteristics of the series circuit or the application of airfield lighting components. This project investigated the emissions produced by LED taxiway edge lights to determine if sufficient emissions are present to warrant further investigations.

## EVALUATION

### METHOD.

CURRENT REQUIREMENTS. The FAA LED Engineering Brief for Alternate Light Sources provides additional requirements for LED fixtures. This document refers to FCC Part 15, Subpart B, covering unintentional radiators. The document (December 2003 rev) states that:

- It is questionable if LED airfield fixtures can be classified by FCC Part 15, Subpart B. Airfield fixtures do not fall into the categories described by Part 15 B.
- For radiated emissions, if the strictest interpretation of any equipment classification is used, the lowest frequency of concern is 30 MHz.
- There is another radiated emission category for equipment that is designed to conduct their radio frequency emissions via connecting wires or cables and that operate starting in the frequency range of 9 kHz (for example, a communications cable or sensor that is on a cable assembly). However, these LED airfield fixtures are not designed for this purpose, on the contrary they are, or should be, designed not to radiate.
- The fixtures that were part of the airfield equipment certification program were classified as a Class A device and tested for nonharmonic emissions with the lowest frequency of concern being 150 kHz.
- There is a general requirement that applies to all equipment or equipment that cannot be classified by Subpart B. This requirement is in a different subpart which applies mainly to Subpart A, Section 15.5:

#### **Section 15.5 General conditions of operation.**

- (b) Operation of an intentional, unintentional, or incidental radiator is subject to the conditions that **no harmful interference is caused** and that interference must be accepted that may be caused by the operation of an authorized radio station, by another intentional or unintentional radiator, by industrial, scientific and medical (ISM) equipment, or by an incidental radiator.
- There is no consideration to the cable plant in which the fixtures are installed. Frequently, there are miles of cable configured in an open loop, which can provide a suitable radiating environment to other cables or into free space.

The general statement of, “no harmful interference is caused,” refers to the fact that equipment shall not cause other equipment to function improperly. But in the case of unclassified equipment, FCC Part 15 does not specify any quantitative numbers or elaborate on test procedures.

With this very basic and general requirement in mind and since there is equipment on the airfield that is affected by frequencies below the FCC limits for classified equipment, suitable methodology must be developed to provide meaningful requirements for these products and the means to test compliance.

The methodology in MIL-STD-461E, Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, provides a basis for a more meaningful test methodology and the means to adapt the testing environment to best suit the application. This is probably the best fit for the project since it guides the designer with the basis for setting up a proper test environment while recognizing the need to customize it for the specifics of the system, where the product will be installed. This is covered in detail in the paragraph titled Conducted Noise Test Methodology.

Generally, there are two categories of effects that these fixtures are likely to produce:

- Harmonic Emissions
- Nonharmonic Emissions

#### HARMONIC EMISSIONS.

Fixture Efficiency. The power supplies in these fixtures include switching elements that result in a nonlinear load to the series circuit. The net result of these effects is that harmonic distortion reduces the efficiency of the fixture, possibly to the point of having a poor power factor, which will waste a portion of the power consumed by the fixture. The efficiency of LED fixtures is one of the advantages in implementing the technology.

Effects of Harmonics on Communications. Generally, the power supply in some LED fixtures feature the charging of a capacitor that is switched in or out at a peak of nearly 60-Hz current conduction. This is easily seen in the waveforms presented in figures 1 and 2. This portion of the conduction cycle on a conventional incandescent circuit has, in the past, been relatively free from noise. The switching action of this charging produces sudden changes in the current into the fixture, at a time when data transmission is occurring. Excessive harmonics produced at this time will degrade the communications of power line carrier products by a strong harmonic of sufficiently high frequency passing through the receiving circuitry of a remote device or modem in the lighting vault.

An example of this case is the following situation: An LED fixture is plugged into a remote switching device as part of an airfield circuit. This switching device is in communication with the equipment in the lighting vault. The signal levels this device receives from the vault, while still well within the usable range, are somewhat weak. In this situation, an LED fixture is actually connected directly to this remote device. Even weak harmonic emissions from this

fixture would appear to the fixture receiving hardware to be strong, since it is directly on its connector, and could easily interfere with the communications. Furthermore, these emissions will also couple on the series circuit, such that they can interfere with other circuits as well.

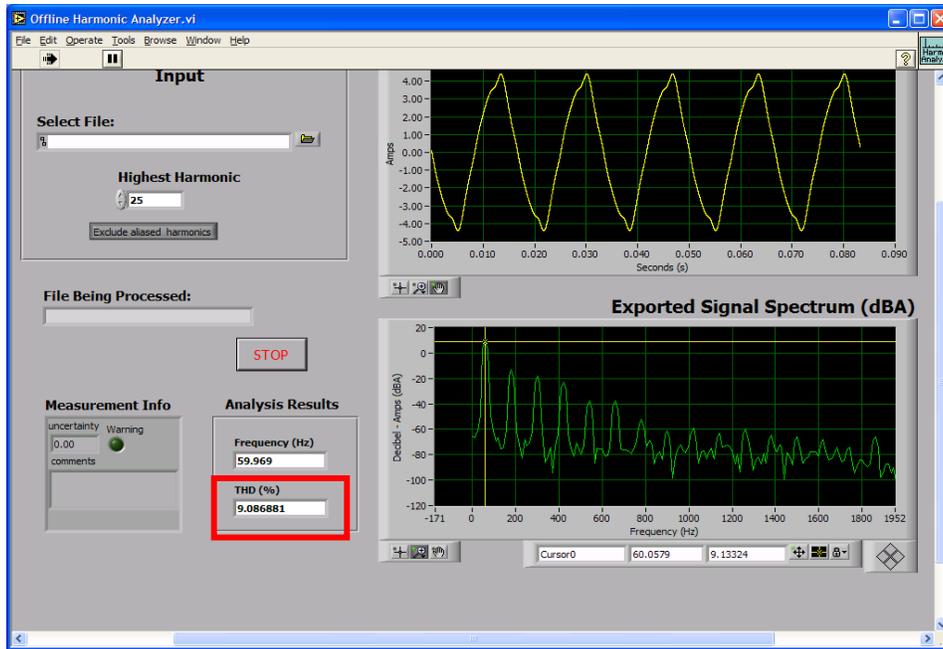


FIGURE 1. HARMONIC ANALYSIS SAMPLE SCREEN

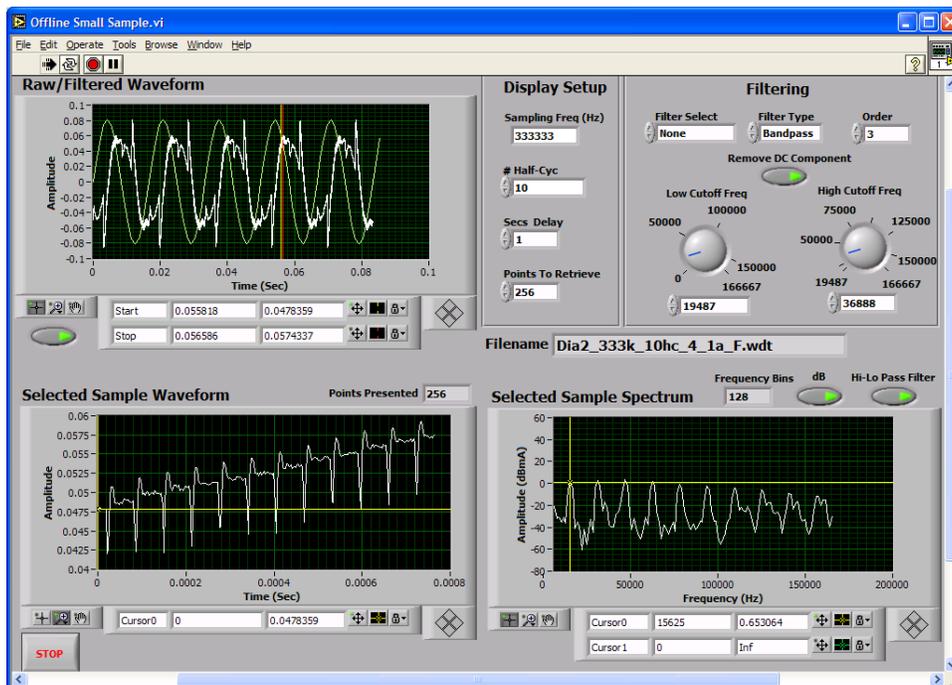


FIGURE 2. NONHARMONIC SPECTRUM SAMPLE SCREEN

Nonharmonic Emissions. In addition to harmonics of the 60-Hz power, there are emissions that are present even in relatively low levels that are not harmonically related. These emissions are either rise time related, (a sharp step in current rich in spectral content) or possibly the result of step response-induced resonance anywhere on the circuit. The presence of these emissions at an inopportune frequency, even in relatively small amplitudes, can easily have the effect of interfering with communications present on the circuit or proximate circuits. The level of these signals need only be in the sub-milliamp range to be visible to communications equipment.

This study was broken into three tasks:

1. Develop an airfield lighting test bed and electrical test methodology for LED taxiway edge lights.
2. Provide quantitative nonharmonic emissions test results for current airfield lighting manufacturer's LED taxiway edge light fixtures.
3. Determine if the current emissions tests referred to in the Engineering Brief, AC 150/5340-24 and AC 150/5345-46B, adequately addresses this level of emissions and recommend changes, if necessary.

Airfield Lighting Circuit Test Bed. Since one of the measurements to be made involves relatively small signals, any test methodology employed must provide a quiet electrical background noise environment. It could be seen from the preliminary look at the fixtures in the laboratory, that matters of gain, noise, and grounding impacted the resulting noisy waveform. In addition, the test setup must present the equipment under test (EUT) with impedance that approximates the actual operating environment, or at least with one that is standardized and from which extrapolation to the actual environment is feasible. There are virtually unlimited numbers of circuit configurations that are combinations of individual lengths of cables and transformers. Also, cable layout, age of the components, transformer type, the amount of water in the conduits pull pits and manholes, and the location and amount of ground leakage are among the many significant factors that determine the electrical characteristics of the circuit. This situation is complicated both by the wide variability of field power source impedances and of laboratory sources such as Variacs, transformers and constant current regulators (CCRs). If the EUT is tested with the incorrect source impedance at the frequencies in question, the measurements are of little value. When considering nonharmonic emissions of a fixture that is connected to the series circuit, the circuit characteristics as they would appear to the fixture must be determined. However, this electrical environment is variable.

The requirement for both a quiet electrical environment and a controlled impedance means that characterization of a fixture must be done on an individual basis with a test setup configured for this purpose, rather than as a field test. In addition, if the test setup is based on industry-accepted methodology, it will provide credible results that can be used as a basis for making recommendations for standards and work with industry to address the issue of compatibility.

MIL-STD-461E, Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, includes standards for emissions quantities and frequencies, including frequencies of interest, and provides a methodology for measurement. Perhaps the most important feature of this standard is that it provides for the methodology and test apparatus to be modified or customized to meet the specific needs of the test requirements. This is clearly the case for testing of airfield lighting products, since it is a unique environment.

It should also be noted that for now it is probably more important to use a methodology based on this standard and determine the emission levels, rather than adopt MIL-STD-461E emission limits as a standard to be met by the equipment. The data collected will then be used as a basis for determining the actual quantitative limits to be recommended.

Controlled Source Impedance—Use of Line Impedance Stabilization Network. To provide a predictable environment to make nonharmonic emissions measurements the impedance that the fixture under test is presented with must be fixed and controlled. A line impedance stabilization network (LISN) provides this capability. Standard LISNs that are used to make measurements are not likely to be useful at the low frequencies of interest and when considering that the environment in question is a series circuit. Off-the-shelf LISNs are generally designed for parallel wiring as well as with a ground reference. In the series circuit world, the current in the loop is the predominant factor.

A relatively simple LISN was designed and built for this test. The design goal was

- to provide a 50-ohm source impedance to the fixture, and
- to decouple the impedance characteristics of the power source feeding the fixture.

The use of LISNs has historically involved compromises between effectiveness and cost/size constraints. LISN design is particularly difficult at very low frequencies, where component size and cost (particularly for inductors) becomes prohibitive. As a result, the industry has tended to accept degradation of the impedance level at low frequencies. Such degradation is apparent in the LISN design specified by MIL-STD-461E in figure 3 and its impedance curve in figure 4.

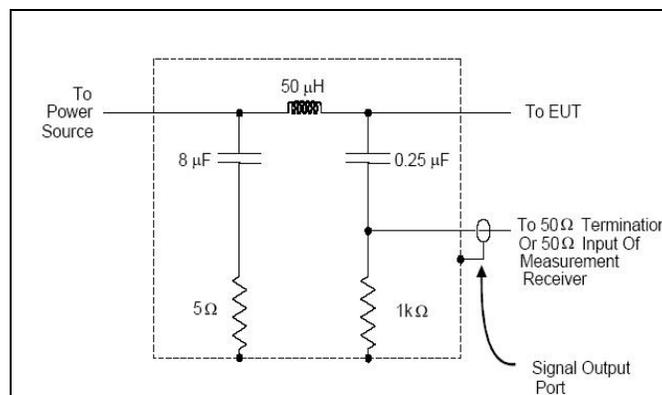


FIGURE 3. MIL-STD-461E LISN DESIGN

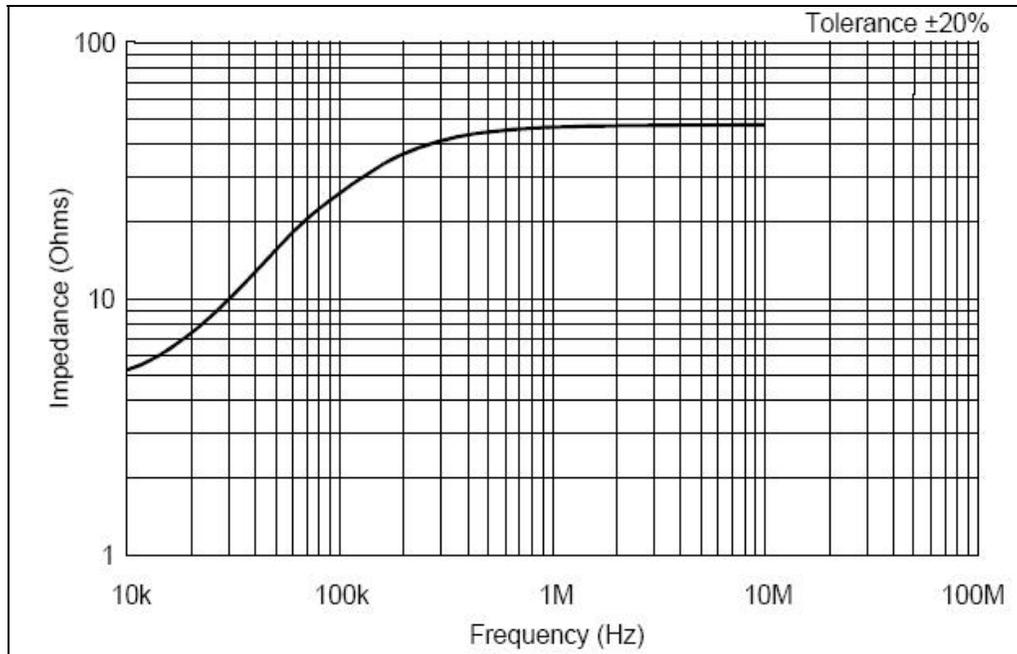


FIGURE 4. MIL-STD-461E LISN IMPEDANCE CHARACTERISTICS

At frequencies in the 10 kHz range, the LISN inductive reactance is so small that the EUT essentially sees the incoming line impedance. At high frequencies, the impedance approaches the design goal of 50 ohms.

The LISN required for nonharmonic emissions by FCC Part 15 includes even less stringent performance requirements, because the measurements do not fall below 150 kHz. A wide variety of LISNs are commercially available, with many designed to meet the requirements of International Electrotechnical Commission (IEC) Standard International Electrotechnical Commission (CISPR) 16-1. Several types claim to meet the requirements of that specification for less than 20 percent impedance degradation at 9 kHz, which represents a considerable improvement over the MIL-STD-461E circuit. Substitution of a CISPR-compliant 9-kHz unit is desirable and in keeping with the flexibility of MIL-STD-461E and possible future extension of compliance testing to IEC or the European Committee for Electrotechnical Standardization (CENELEC) standards. (The test setup to be described below effectively meets the 9-kHz standard without use of a separate LISN.)

As in other power equipment, the actual operating impedance seen by the lamp electronics is likely to be highly variable; however, 50 ohms is a reasonable test value, since the characteristic impedance of the transmission line loss represented by the series loop wiring will be in the 50-ohm range.

Tests using the CE101 methodology of MIL-STD-461E (Nonharmonic Emissions, Power Leads, 30 Hz to 10 kHz) involves the use of a current probe to measure the EUT emissions for comparison with the relevant limits. If the EUT emissions are voltage-limited, extremely high terminating impedance will result in falsely low current readings, while extremely low impedance will result in current readings that are higher than would be present at 50 ohms.

For the methodology starting at 10 kHz and up, CE102 of MIL-STD-461E, voltage is measured across the nominal 50-ohm LISN output. If the actual LISN impedance is 50 ohms, the corresponding current will be V/50 and a seamless transition from the current to voltage measurement will apply. In view of the impedance characteristics of the MIL-STD-461E LISN in figure 4, it can be seen that this is obviously not the case and only marginally true for the CISPR variety. For initial evaluation purposes, it is better to extend use of the current measurement to 150 kHz to encompass the region of major concern.

EQUIPMENT.

All tests were performed at the FAA William J. Hughes Technical Center, Atlantic City, New Jersey, at the airfield lighting test bed. Table 1 shows the equipment used for this evaluation.

TABLE 1. EQUIPMENT

Equipment	Supplier	Model
Data Acquisition system	National Instruments	DAQ-6052E
Analysis Software	National Instruments	Labview 7.1, Signal Analysis package, Custom Applications
Spectrum Analyzer	Rohde and Schwarz	FSH3
LISN, series circuit	CSI, Inc.	
Digital Trigger Signal Circuit	CSI, Inc.	
Receiver	AOR	AR5000A +3B
Scope	Fluke	123A
Current Probe, for trigger	Fluke	i200

NONHARMONIC EMISSIONS TEST PROCEDURES.

The region below 100 kHz is often not covered by commercial spectrum analyzers. The widest range (and very expensive) analyzers extend down to the 9 kHz CISPR limit, or even lower. Since the gaps between 60-Hz harmonics are of interest, the resolution should extend to a fraction of 60 Hz, down to at least 10 Hz and preferably lower. Another problem with a sweep-based spectrum analyzer is that the frequencies that are displayed are the result of an averaging over time and cannot take into account the actual emissions magnitude that occurs at discreet, short intervals of time.

For the present application, an analog data acquisition card in conjunction with computer-based spectrum analysis software was used. The National Instruments 6052E data acquisition system was used for the project. This product has a sampling rate of 333,333 samples per second, allowing measurements up to 166.667 kHz. The analog to digital converter has a resolution of 16 bits, resulting in a dynamic range of greater than 90 dB (1 part in 65,536, or  $2^{16}$ ). This data acquisition system provides samples to a software analysis package that runs on a personal computer (PC). For this project, Labview with the signal processing toolkit was used to develop data acquisition and analysis applications. The sample files acquired are processed by the

application that was developed to extract the frequency characteristics of the measurements. In addition, a Rohde and Schwarz FSH3 spectrum analyzer was used to measure emissions above 150 kHz.

Successful measurement of small signals at the desired resolution depends on careful attention to the test setup isolation, grounding, and instrument coupling. These aspects are discussed below.

The test setup for MIL-STD-461E operates the EUT directly from the line via LISNs (one network in each side of the line). However, the typical environment is likely to require additional isolation from the line to measure at and below the 1-milliamp level. Furthermore, the low volts/milliamp output of most current probes, and their susceptibility to stray magnetic fields, may pose a problem that is best solved by the alternate method of sampling the current across a known low resistance.

For these measurements, a Variac was used to control the lamp current. This entire environment must be set up on a suitable ground plane consisting of a sheet of metal, with the only ground connection to the instrumentation shown in figure 5. Layout and cable routing must be designed with care to provide the best results.

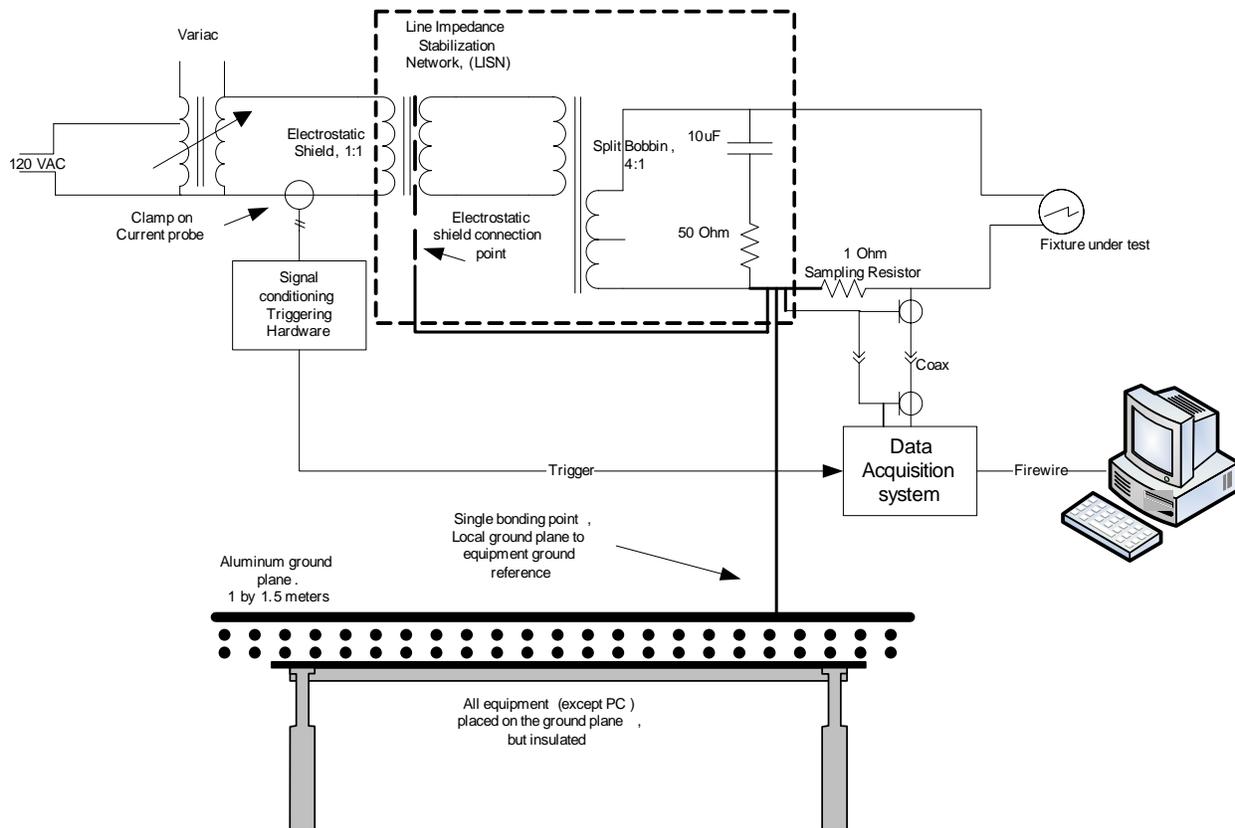


FIGURE 5. PROJECT TEST BED DESIGN

The resistive sampling is shown in differential four-terminal form. A high degree of isolation from line noise is provided by the use of an electrostatically shielded transformer designed for this purpose. A second step down isolation transformer of split bobbin design is also used. The 4:1 turns ratio helps with reducing the maximum of 120 volts present on the Variac to more like 30 volts, making it easier to control. Additionally, the split bobbin design inherently provides a large leakage inductance, which provides the important function of isolating the impedance of the power system from the impedance derived from the 50-ohm resistor and 10- $\mu$ F capacitor high pass network shown in figure 5. This high pass network provides a known impedance characteristic that is presented to the EUT so that current measurements are made across the 1-ohm resistor. The voltage developed across this resistor, in volts, represents the circuit current in amps.

This approach has the additional benefits of permitting the use of direct connection of one side of the EUT circuit to a local ground plane through the sampling resistor, thus permitting current sampling with virtually zero common mode voltage. This LISN, which is outlined in the dashed area of figure 5, shows greatly improved low frequency response. The impedance characteristics are shown in figure 6.

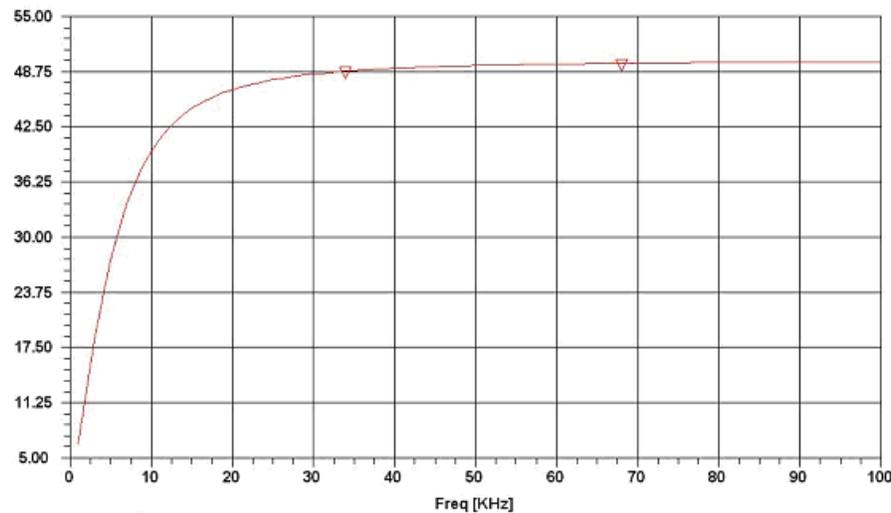


FIGURE 6. TEST BED LISN IMPEDANCE

Also provided is a means to consistently trigger the data acquisition at a known time. A simple current probe is placed on one of the power leads, as shown in figure 5. A sample of the raw current is passed through a signal conditioning circuit to provide a positive going pulse at the 60-Hz rate. The phase relationship of this pulse to the zero crossing of the current is controlled and very stable, to within about 100 microseconds. This will provide a stable phase coherent trigger source to ensure that the captured waveforms start at the same place, preventing jitter from noise.

TEST ENVIRONMENT DEFINITIONS. There are many terms and conversions that come into play with these kinds of measurements. Generally, decibel (dB) measurements are used in the emissions world. The use of dB, which is a logarithmic scale, better allows the signals that are

very small to be compared to the signals that are very large. When using dB for this application, the units of dBA (decibel amps), dBmA (decibel milliamps), or dBμA (decibel microamps) will be used.

The formula for dBA is:

$$dBA = 20 * \log(\text{current, in amps})$$

This means that 0 dBA is 1 amp, or a measurement of 6 dBA is about 2 amps. The rule of thumb is an increase of 6 dB is about twice the magnitude. Considering the formula, a signal that is 20 dBA stronger than another signal is in fact 10 times the amplitude. Or a signal that is weaker than another signal by -40 dBA is 100 times weaker in magnitude.

The use of dBmA or dBμA simply changes the reference, such that 0 dBmA is 1 milliamp, and 0 dBμA is 1 microamp. These are used for convenience to better fit the scaling to the application.

Table 2 is a lookup table that can be used to convert current to dBA and vice versa.

TABLE 2. DECIBEL TO CURRENT CONVERSION

For dBA (decibel Amps)

dBA = 20 \* LOG(CURRENT)

dBuA	dBmA	dBA	uA	dBuA	dBmA	dBA	uA	dBuA	dBmA	dBA	mA	dBuA	dBmA	dBA	Amps
0	-60	-120	1	40	-20	-80	100	80	20	-40	10	120	60	0	1
1	-59	-119	1.11	41	-19	-79	112.2	81	21	-39	11.22	121	61	1	1.12
2	-58	-118	1.25	42	-18	-78	125.9	82	22	-38	12.59	122	62	2	1.25
3	-57	-117	1.41	43	-17	-77	141.3	83	23	-37	14.13	123	63	3	1.41
4	-56	-116	1.58	44	-16	-76	158.5	84	24	-36	15.85	124	64	4	1.58
5	-55	-115	1.77	45	-15	-75	177.7	85	25	-35	17.78	125	65	5	1.77
6	-54	-114	1.99	46	-14	-74	199.5	86	26	-34	19.95	126	66	6	1.99
7	-53	-113	2.23	47	-13	-73	223.9	87	27	-33	22.39	127	67	7	2.23
8	-52	-112	2.51	48	-12	-72	251.2	88	28	-32	25.12	128	68	8	2.51
9	-51	-111	2.81	49	-11	-71	281.8	89	29	-31	28.18	129	69	9	2.81
10	-50	-110	3.16	50	-10	-70	316.2	90	30	-30	31.62	130	70	10	3.16
11	-49	-109	3.54	51	-9	-69	354.8	91	31	-29	35.48	131	71	11	3.51
12	-48	-108	3.98	52	-8	-68	398.1	92	32	-28	39.81	132	72	12	3.98
13	-47	-107	4.47	53	-7	-67	446.7	93	33	-27	44.67	133	73	13	4.46
14	-46	-106	5.01	54	-6	-66	501.2	94	34	-26	50.12	134	74	14	5.01
15	-45	-105	5.62	55	-5	-65	562.3	95	35	-25	56.23	135	75	15	5.62
16	-44	-104	6.31	56	-4	-64	631	96	36	-24	63.1	136	76	16	6.31
17	-43	-103	7.07	57	-3	-63	707.9	97	37	-23	707.9	137	77	17	7.07
18	-42	-102	7.94	58	-2	-62	794.3	98	38	-22	79.43	138	78	18	7.94
19	-41	-101	8.93	59	-1	-61	891.3	99	39	-21	89.13	139	79	19	8.91
dBuA	dBmA	dBA	uA	dBuA	dBmA	dBA	mA	dBuA	dBmA	dBA	mA	140	80	20	10
20	-40	-100	10	60	0	-60	1	100	40	-20	100				
21	-39	-99	11.22	61	1	-59	1.12	101	41	-19	112.2				
22	-38	-98	12.5	62	2	-58	1.25	102	42	-18	125.9				
23	-37	-97	14.13	63	3	-57	1.41	103	43	-17	141.3				
24	-36	-96	15.85	64	4	-56	1.58	104	44	-16	158.5				
25	-35	-95	17.78	65	5	-55	1.77	105	45	-15	177.8				
26	-34	-94	19.95	66	6	-54	1.99	106	46	-14	199.5				
27	-33	-93	22.39	67	7	-53	2.23	107	47	-13	223.9				
28	-32	-92	25.12	68	8	-52	2.51	108	48	-12	251.2				
29	-31	-91	28.18	69	9	-51	2.81	109	49	-11	281.8				
30	-30	-90	31.62	70	10	-50	3.16	110	50	-10	316.2				
31	-29	-89	35.48	71	11	-49	3.54	111	51	-9	354.8				
32	-28	-88	39.81	72	12	-48	3.98	112	52	-8	397.1				
33	-27	-87	44.67	73	13	-47	4.46	113	53	-7	446.7				
34	-26	-86	50.12	74	14	-46	5.01	114	54	-6	501.2				
35	-25	-85	56.23	75	15	-45	5.62	115	55	-5	562.3				
36	-24	-84	63.1	76	16	-44	6.31	116	56	-4	631				
37	-23	-83	70.79	77	17	-43	7.07	117	57	-3	707.9				
38	-22	-82	79.43	78	18	-42	7.94	118	58	-2	794.3				
39	-21	-81	89.13	79	19	-41	8.91	119	59	-1	891.3				

MEASUREMENT OF HARMONIC EMISSIONS. A Labview measurement application to graphically plot harmonics of the fixture current was developed for this project. The setup is shown in figure 5. The current for the fixture was set to each of the 7 current steps that are used with both 3- and 5-step CCRs. When the application runs, the software on the PC enables the data acquisition system. For these measurements, the system takes samples at the rate of 333,333 samples per second, or about 1 sample per 3 microseconds. In real time, the system then acquires the samples, captures them to the PC memory, and then the application software shows the waveform in the time domain. The software also provides a graphical depiction of the strength of the number of harmonics desired and does the calculation for total harmonic distortion (THD) of the waveform. The detailed measurements for each fixture and each current step is shown in figures 7a through 7e, showing total distortion harmonics for each fixture.

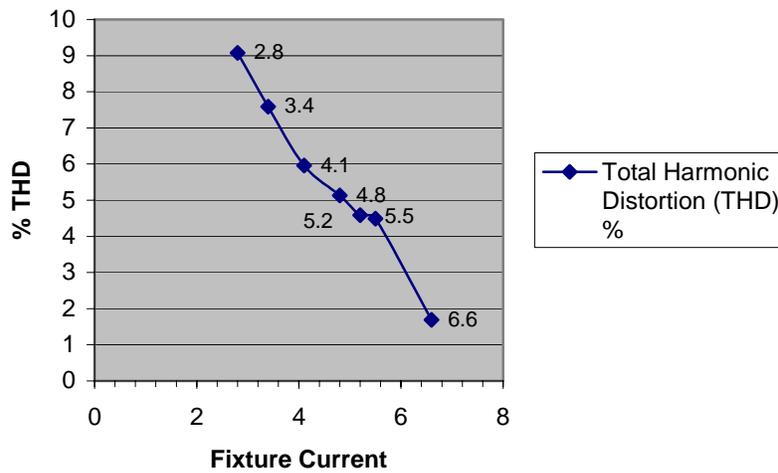


FIGURE 7a. FIXTURE A TOTAL HARMONIC DISTORTION

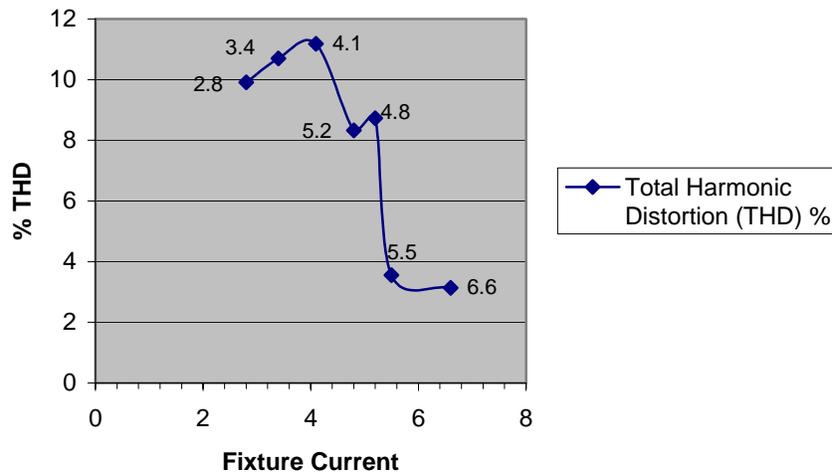


FIGURE 7b. FIXTURE B TOTAL HARMONIC DISTORTION

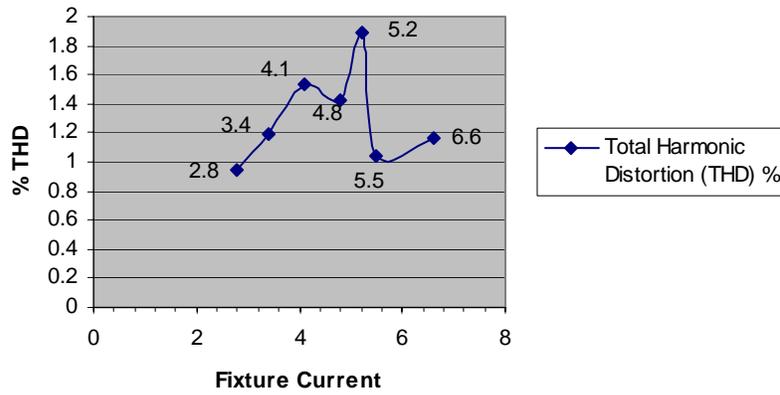


FIGURE 7c. FIXTURE C TOTAL HARMONIC DISTORTION

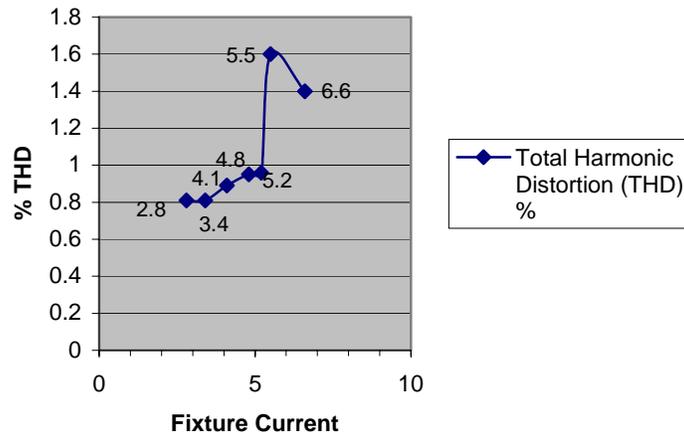


FIGURE 7d. FIXTURE D TOTAL HARMONIC DISTORTION

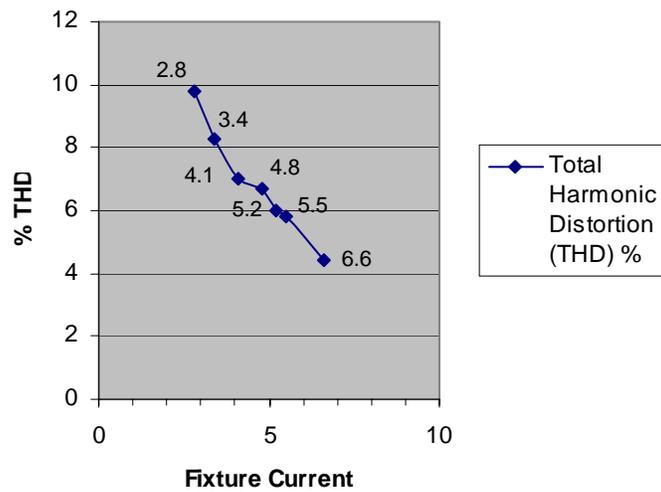


FIGURE 7e. FIXTURE E TOTAL HARMONIC DISTORTION

MEASUREMENT OF NONHARMONIC EMISSIONS. The measurements for the higher frequencies and lower levels of signals were done in a slightly different way. As shown in figure 8, there is an additional high pass filter included in between the sampling resistor and the data acquisition system. By attenuating the 60 Hz by 40 dB or a factor of 100, the gain amplifier on the data acquisition system was set to be more sensitive, allowing single-bit resolution of about 3 microamps, placing the noise floor at about -50 dBmA, and this is more or less what is observed in figure 1.

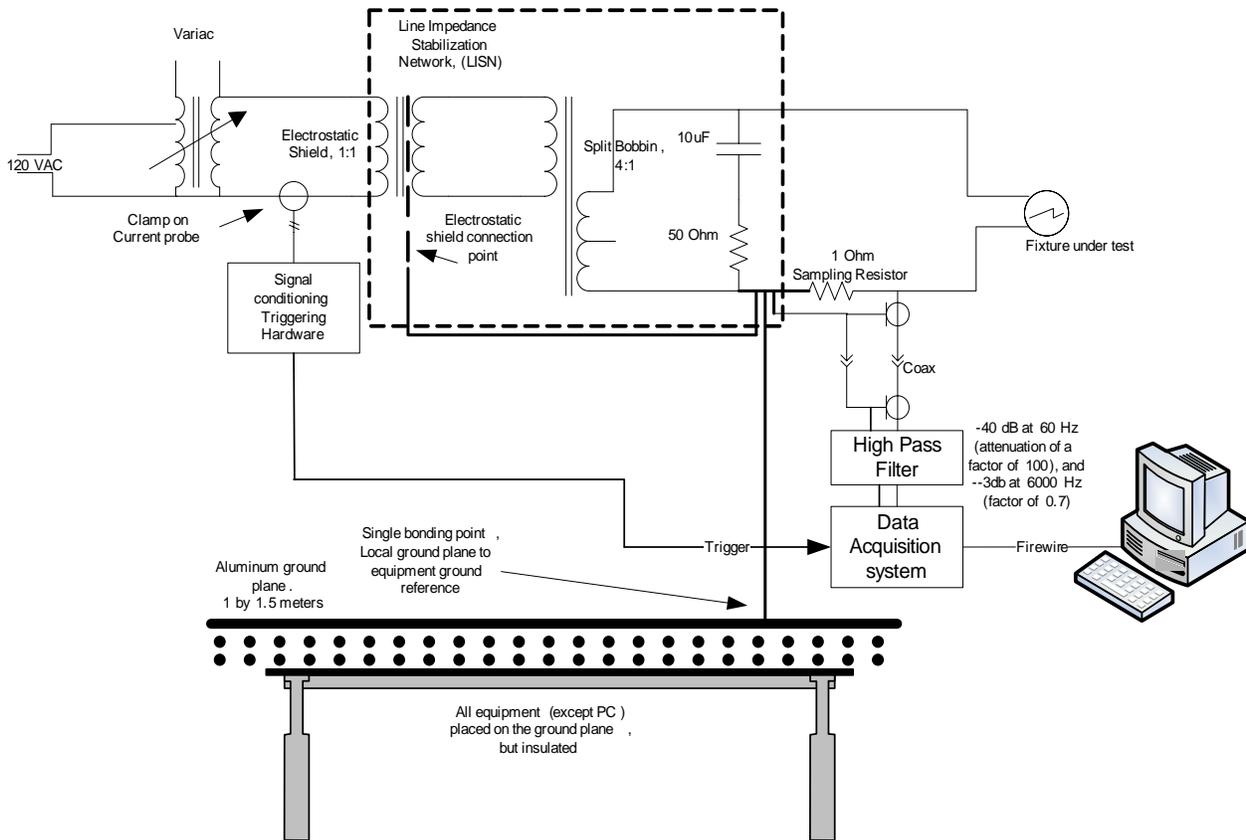


FIGURE 8. NONHARMONIC EMISSION TEST SETUP

The spectrum analysis application running on the PC captured the samples running at the maximum rate of 333,333 samples per second, and first displayed them on the time domain window in the upper left of figure 2.

The special feature of this application is that it must be recognized that the emissions actually can occur at different discreet times during the alternating current (ac) cycle. Merely placing the signal into a spectrum analyzer or using a very wide window does not characterize the nature of the emission. The application used here allows a cursor to be placed on the time domain captured waveform, and a spectral analysis is done only on a defined window of the sample. This allows one to see that for some fixtures, the emissions are different at different parts of the ac cycle.

The portion of the time domain that is being analyzed is displayed in the lower left window. In that window, a closer look of the time domain signal can be seen. In the lower right window, the spectrum view displays the amount of current, at specific frequencies.

It also must be noted that the frequency characteristics of the high pass filter are compensated in the frequency domain displayed in the lower left of figure 2. The inverse of the formula that characterizes the high pass filter frequency response is applied to the signal levels at the frequencies involved, thus normalizing as a function of frequency amplitudes at about 6 kHz

HARMONIC EMISSIONS SCREEN. A sample screen of a harmonic measurement is shown in figure 1. The upper right window shows the input signal under test, which was captured from the data acquisition system. The current waveform is shown and is presented in amps. Highlighted in red is the calculation of THD. The lower right window labeled Exported Signal Spectrum shows the amount of spectral energy at the specific harmonic frequencies shown. Harmonics are shown in dBA. Typically, the fundamental of 60 Hz is the first signal seen, and in this case, the cursor is shown at the 60-Hz position, with strength of 9.13 dBA, displayed in the numerical window under the spectrum trace. In this case, 9.13 dBA is a little more than 2.8 amps, which is approximately the current step for this example; the odd harmonics are predominantly seen here, at the next peak (after 60 Hz) at 180 Hz.

NONHARMONIC EMISSIONS SCREEN. This screen provides the detail for emissions of frequencies that are not necessarily harmonically related to 60 Hz (see figure 2). For these measurements, the current sample is passed through a high pass filter before entering the data acquisition system. This high-pass filter has attenuation at 60 Hz of 40 dB or about a factor of 100. This was done to allow more resolution of smaller signals, by increasing the gain of the data acquisition system input amplifier, without overloading it. This filter also has the effect of shifting the phase of 60 Hz by about 90 degrees lagging or about 4.33 milliseconds. The higher frequencies are not phase shifted.

For this reason, an external trigger, which starts the data acquisition at the actual zero crossing of the current, is used. Looking at the time domain waveform in the upper left of the screen, the white trace is the current sample through the high-pass filter. A synthesized 60 Hz can also be seen in green on that window. The synthesized signal starts at the real zero crossing and has no effect on any measurement. Its purpose on the screen is to provide a reference for viewing the actual phase of the 60-Hz signal. A cursor is also visible on the same window. This cursor is used to locate a selected sample area of which to perform the spectrum analysis. This allows specific spectrum characteristics to be identified at specific locations in time. The yellow cursor is the start of the sample and the red cursor is the end of the sample to be examined. In this example, the cursor is placed in a location where there is an emission of relatively high strength. It appears on the white waveform to be just before the peak of the 60-Hz signal, but because of the phase shift in the 60 Hz, referring to the green synthesized waveform, it can be seen that this high frequency is in fact just after the peak of the 60-Hz signal.

The lower left window, Selected Sample Waveform, is a “zoom in” of what is bounded by the cursors in the Raw/Filtered Waveform above it. Depending on the waveform, this can be additionally zoomed in both in time and amplitude to allow a close look at the signal in time.

The axes are labeled in amps and time. In the lower right window, the exported signal spectrum shows the frequencies present in the selected sample waveform. There is compensation in the magnitude of the frequencies displayed to account for the roll off characteristics of the high pass filter used for this measurement. The strength of the frequencies is shown in dBmA, where a signal of 0 dBmA is equal to 1 milliamp. In this example, there is a signal at 15.625 kHz at a little more than 0 dBmA, followed by its harmonics at 31.250, 46.875, 62.500, 78.125 kHz, etc.

The filtering area is used to place a software digital filter of configurable design in line with the incoming signal. This is not used for signal measurements but for analysis of the effects of the signal waveforms on typical filters used in the front end of the receiving hardware, to see what these systems would have to contend with if these emissions are present on the circuit.

## RESULTS.

BASELINE CIRCUIT MEASUREMENTS. Before measurements on the fixtures were conducted, a baseline of the system without fixture was conducted. There is always a level of harmonics and other emissions present in the incoming power system. Passing it through the Variac and isolation transformers will generally reduce ground-related noise; however, there is a residual characteristic that is seen in figures 9 and 10. Odd harmonics characteristics are seen no stronger than -40 dBA and below 1 kHz. Harmonics are below the -70 dBA range. This is typical of what is seen of power through the magnetics of transformers. Figure 9 also shows the total harmonic distortion, on the order of 0.4%. While this is not absolutely perfect, it is well below THD that will be seen as a result of the fixtures. The spectrum measurement in figure 10 shows in the domain view the small bend in the current that is exaggerated by the high pass filter. This is the characteristic of core magnetization in the transformers and must be kept in mind for the rest of the samples. Also, it shows that there is a background of extremely small spectral components, the strongest of which are in the -35 dBmA range or about 20 microamps; not a significant factor for these measurements. Fixtures from five current lighting manufacturers were obtained for testing and were labeled A-E.

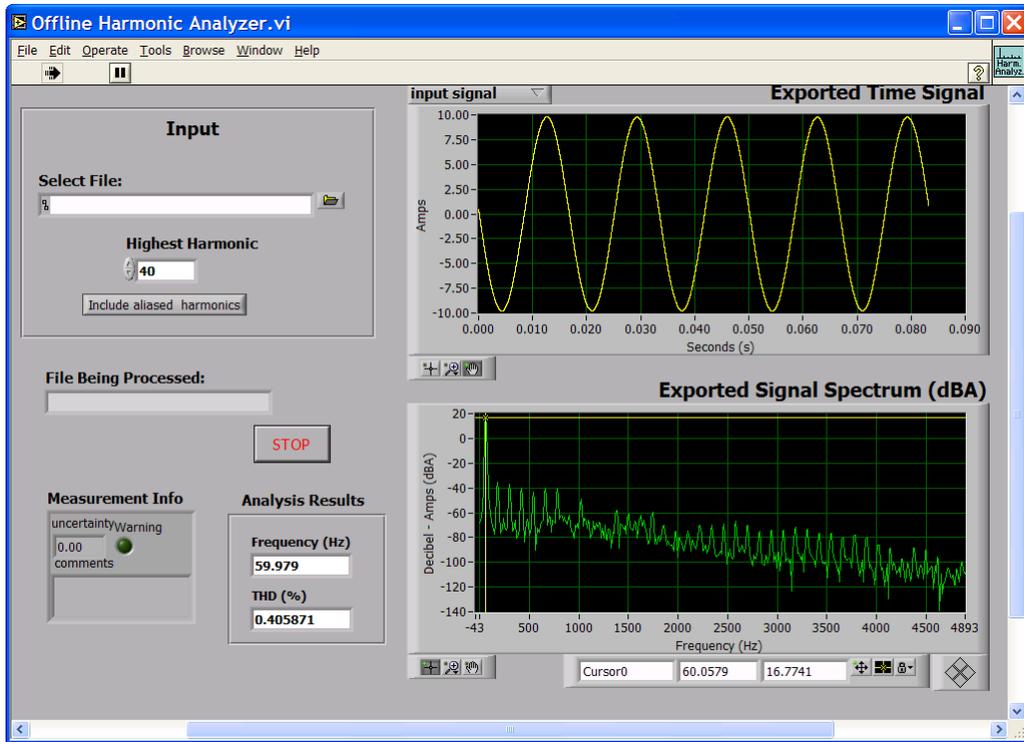


FIGURE 9. BASELINE HARMONICS—NO FIXTURES

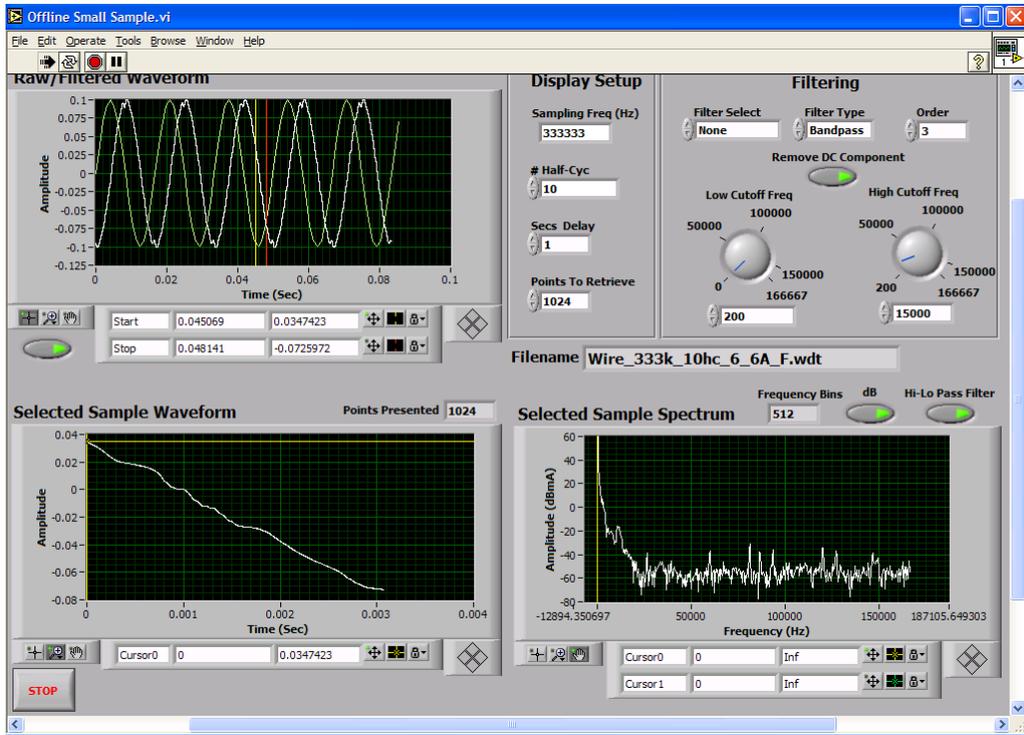


FIGURE 10. BASELINE SPECTRUMS

## FIXTURE A.

Harmonic Measurements. Refer to figure 11 for the 2.8-amp step for the harmonic measurement of this fixture. The THD can be seen in figure 7a. This fixture shows a step characteristic near the peak of the current, resulting in a worst-case THD of about 9% at 2.8 amps. Even so, there are odd low-order harmonics that are below -40 dBA (10 mA) before they reach the 13<sup>th</sup> harmonic and are near -70 dBA at about 2.0 kHz. When the current is stepped up to 6.6 amps, the lower harmonics (which contained more energy at lower step) drop off more rapidly while the higher-order harmonics are of similar strength, resulting in the THD of only 1.7%.

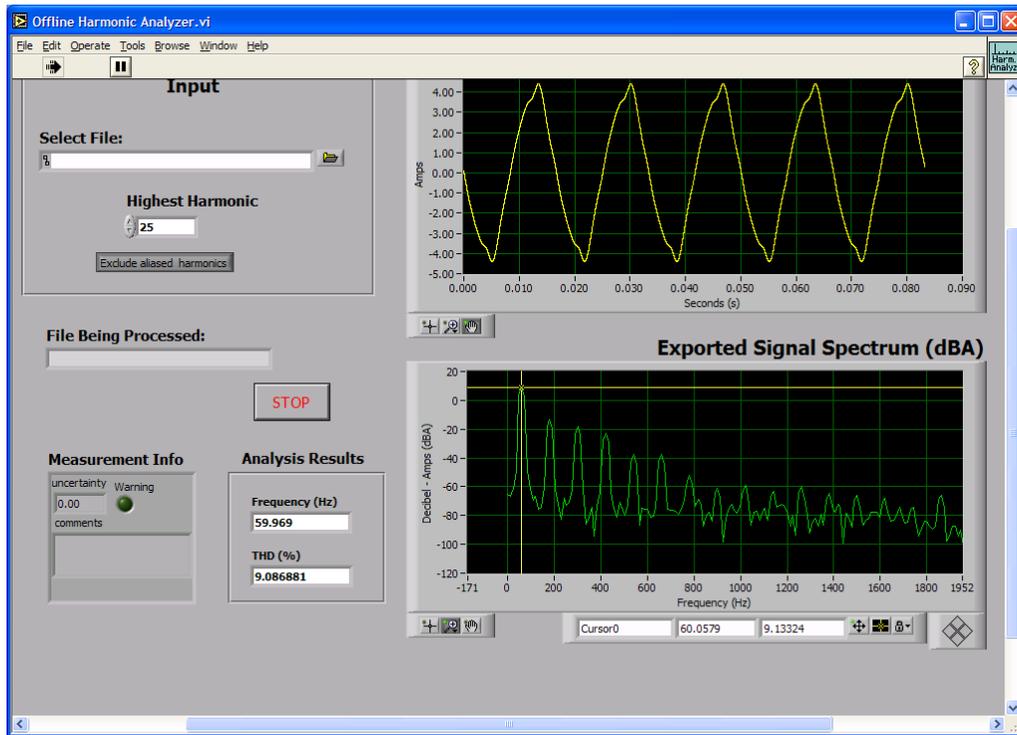


FIGURE 11. FIXTURE A HARMONICS, 2.8 amps

Nonharmonic Measurements. The emissions spectrum is shown in figure 12. For the most part, no nonharmonic emissions, except the low-order harmonics, are seen. Generally, the -50 dBmA noise bed is seen with some consistent unrelated low-level peaks in the -40 dBmA range (10 microamps).

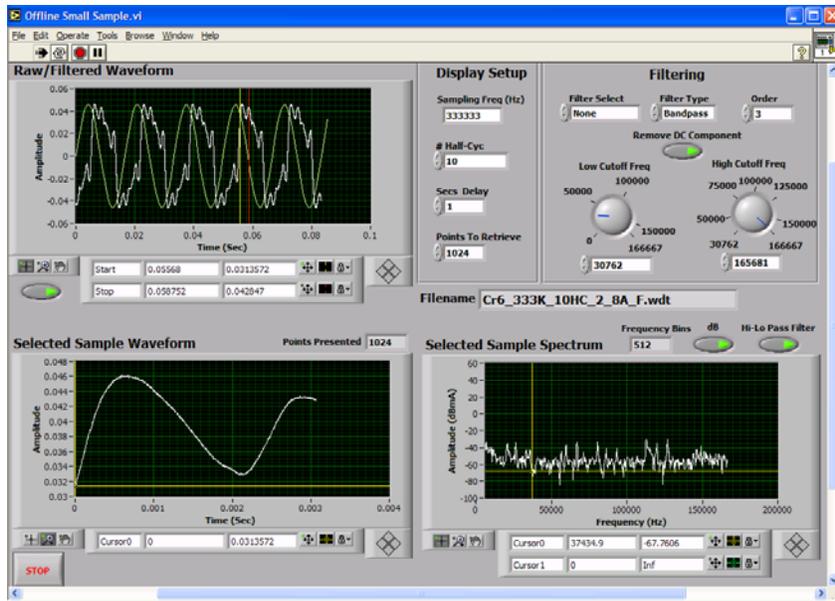


FIGURE 12. FIXTURE A SPECTRUM, 2.8 amps

FIXTURE B.

Harmonic Measurements. Refer to figure 13 for the 2.8-amp step for the harmonic measurement of this fixture. The THD is shown in figure 7b. THD on this fixture actually increases from about 10% at 2.8 amps to more than 11% at 4.1 amps, and then down to about 3% at 6.6 amps.

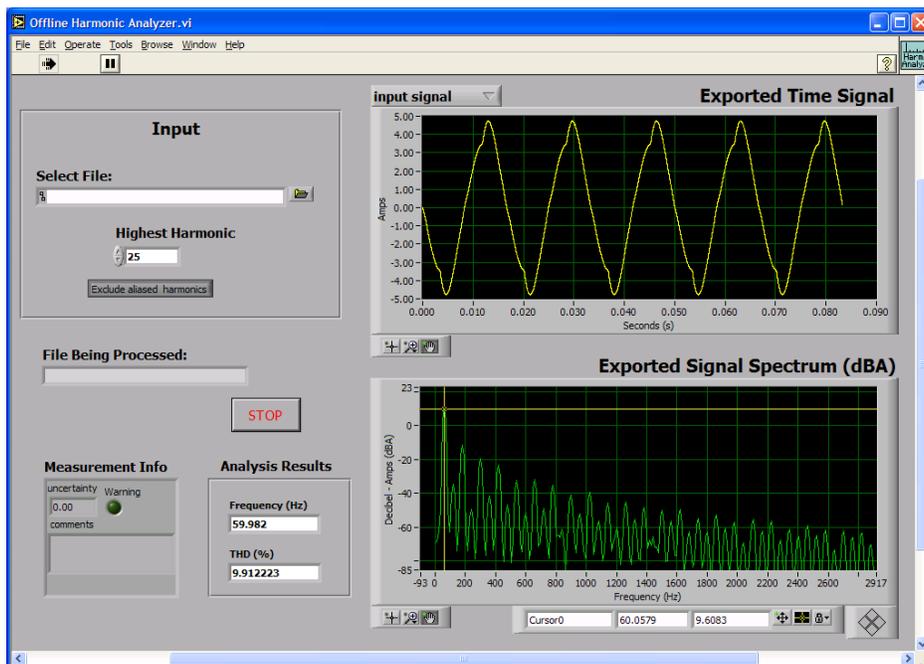


FIGURE 13. FIXTURE B HARMONICS, 2.8 amps

Besides the odd harmonic content, this fixture also has substantial even harmonics that can be seen on the captures in figure 14. The even harmonics subside, as the constant current regulator step, is increased while the odd harmonics stay more or less the same. An illustrative plot of this is included in figure 14 for clarity. Some even and odd harmonics are labeled. Typically, even harmonics are caused by asymmetry of the signal that is there, which is a residual direct current (dc) component from more current being drawn during one half of the cycle than the other half of the cycle. This can frequently be caused by an internal half wave rectifier power supply.

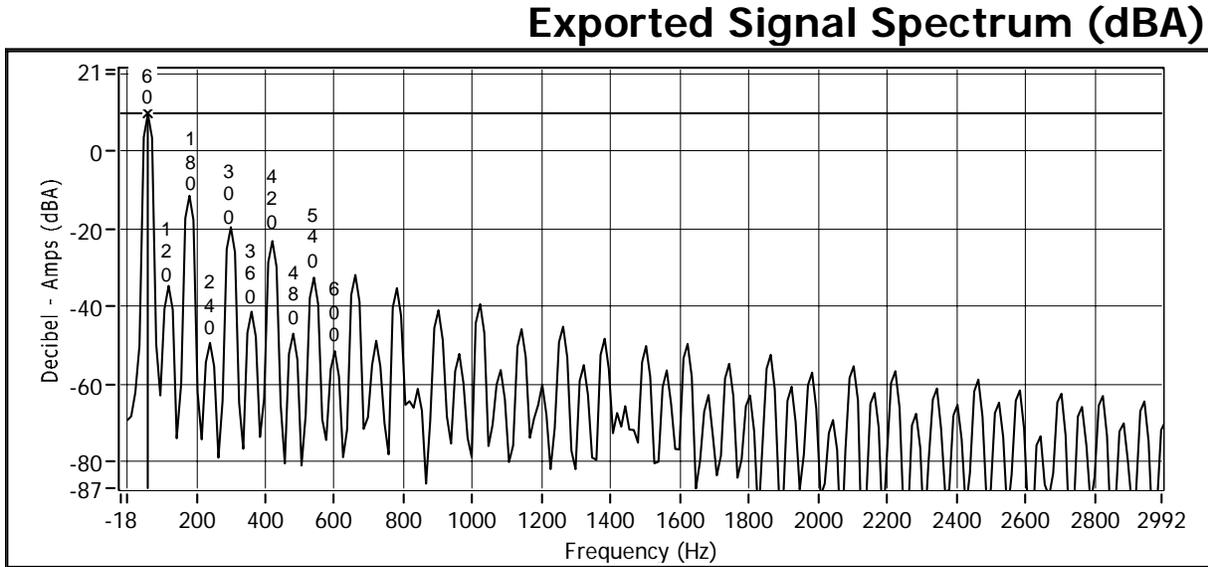


FIGURE 14. FIXTURE B EVEN AND ODD HARMONICS DETAIL

Nonharmonic Measurements. The emissions spectrum is shown in figure 15. This fixture showed a varied set of characteristics. Looking through the spectrum figures, it can be seen that there are high frequency emissions that are present during a majority of the time on the ac cycle. Furthermore, the frequencies change as a function of the current setting. The characteristic of this emission in the time domain is shown very well in figure 16 at a step of 4.1 amps. A portion of the time domain signal is expanded in the selected sample waveform window in the lower left of the image. This shows a characteristic impulse shape with a peak-to-peak value of around 10 milliamps. This impulse type emission includes strong even and odd harmonics of nearly equal magnitude. This can be seen in the selected sample spectrum window. The fundamental of this frequency is around 15 kHz, with harmonics across the board of the window up to 156 kHz and higher.

At 4.8 amps in figure 17, the frequency of the emission changes to about 52 kHz, with a similar impulse shape and also about 10 milliamps peak to peak in magnitude. It shows odd and even harmonics at 104 and 156 kHz.

In figure 18, the frequency changes again, to a fundamental of about 39 kHz, and still includes odd and even harmonics.

Also noteworthy on the same current step, the emissions changed characteristics slightly later in the ac cycle, shifting up in frequency to about 42 kHz, as shown in figure 19.

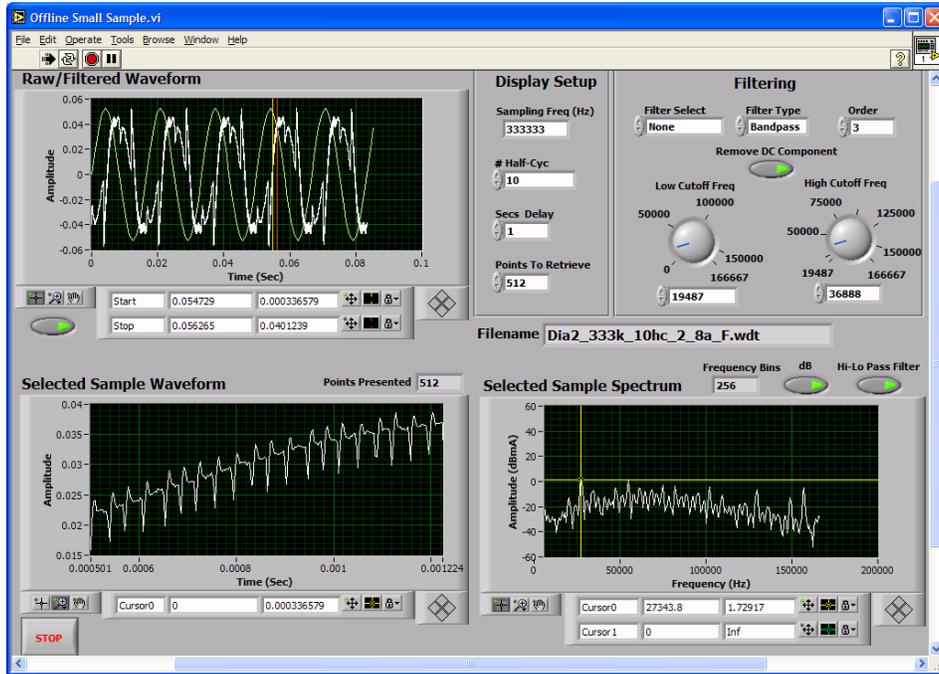


FIGURE 15. FIXTURE B SPECTRUM, 2.8 amps

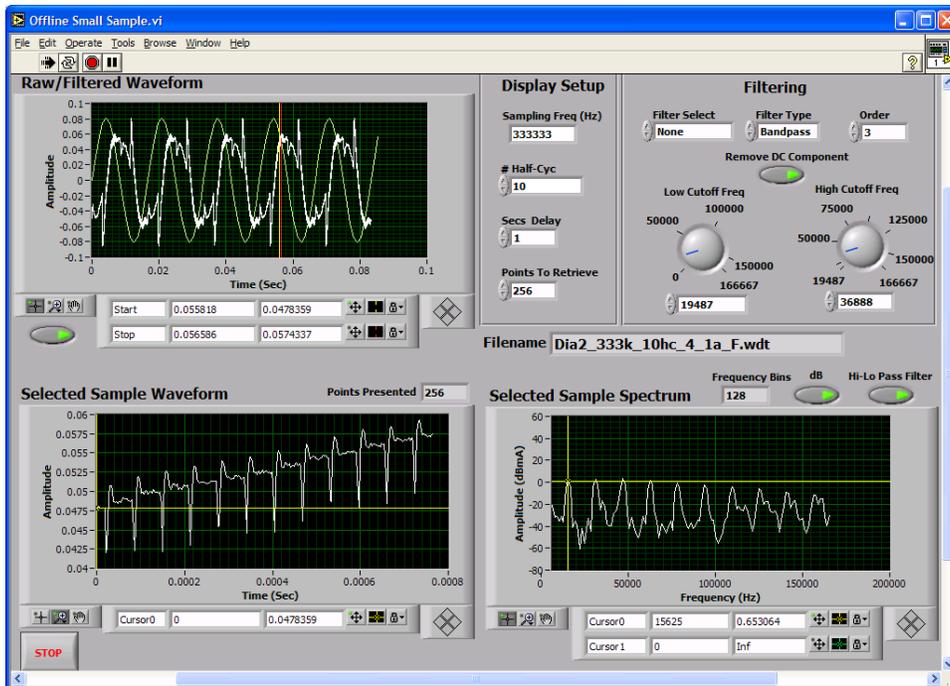


FIGURE 16. FIXTURE B SPECTRUM, 4.1 amps

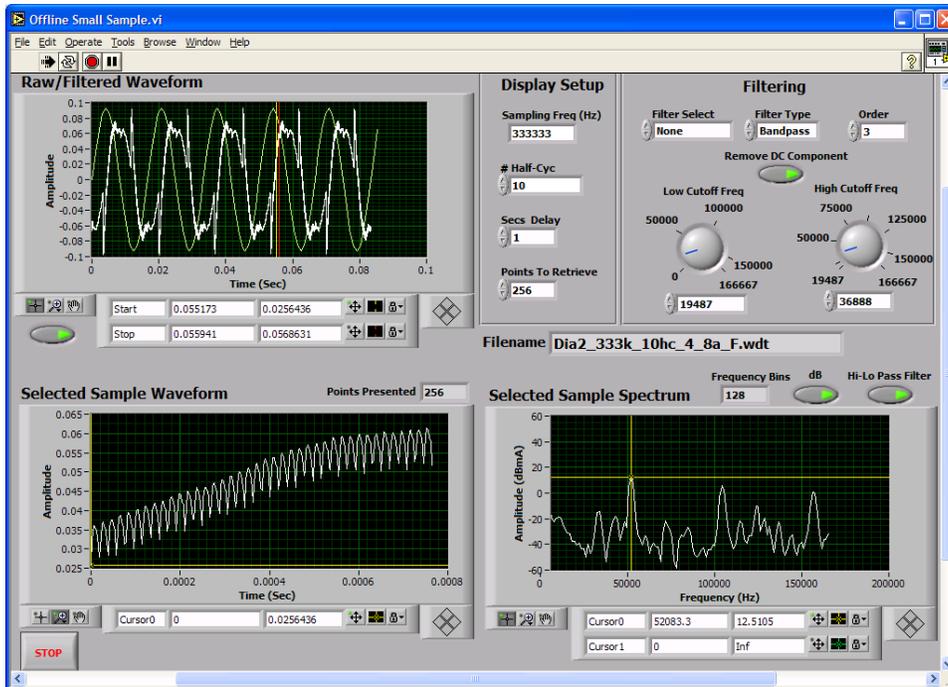


FIGURE 17. FIXTURE B SPECTRUM, 4.8 amps

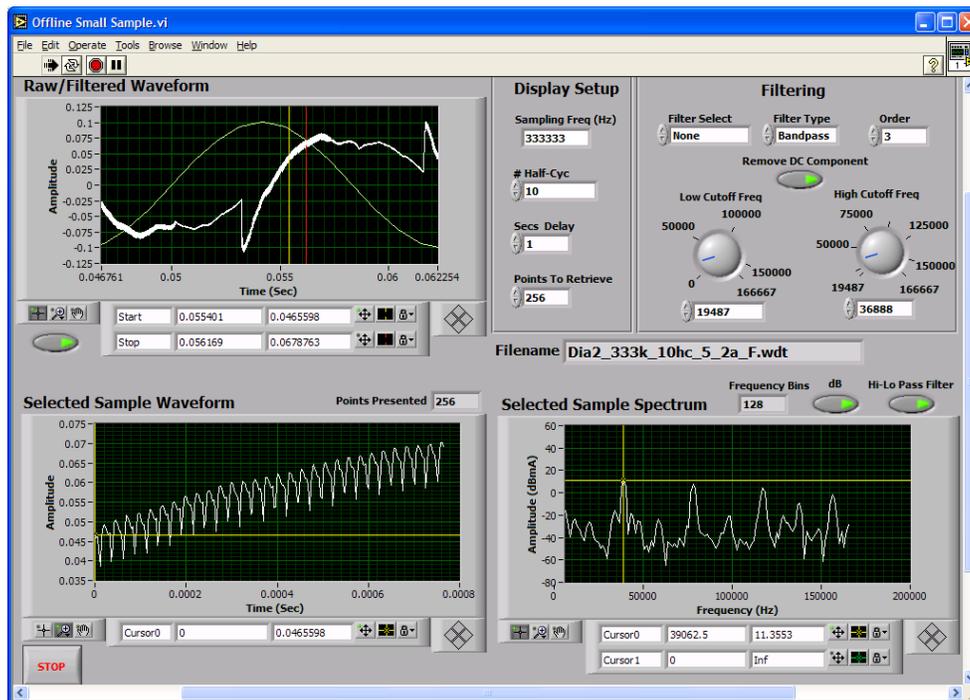


FIGURE 18. FIXTURE B SPECTRUM, 5.2 amps  
(Frequency changes during cycle)

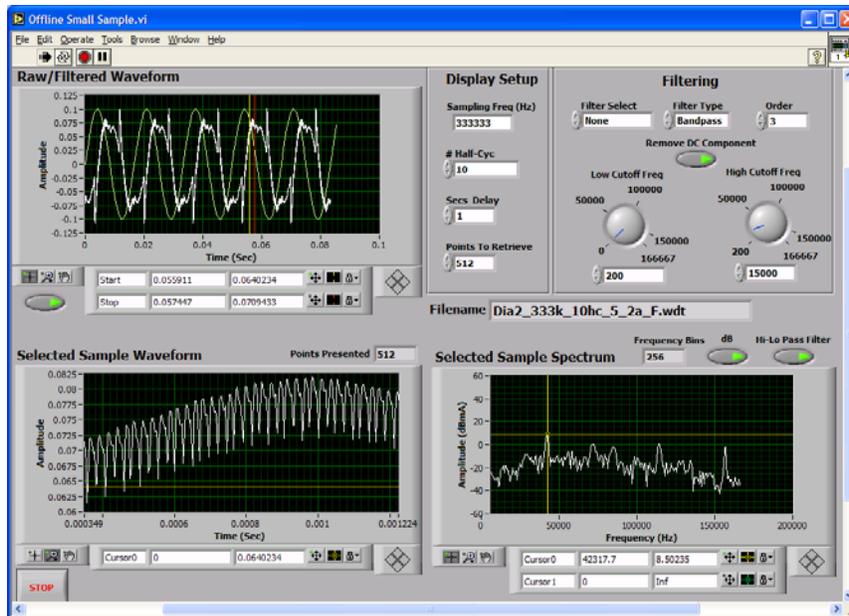


FIGURE 19. FIXTURE B, 5.2 amps, WITH SHIFTED EMISSION FREQUENCY

FIXTURE C.

Harmonic Measurements. Refer to figure 20 for the 2.8-amp step for the harmonic measurement of this fixture. The THD is shown in figure 7c. This fixture showed THD between about 1% and 2% between 2.8 and 6.6 amps. The distortion, while low, showed its lowest distortion at 2.8 amps, and its highest at 5.2 amps.

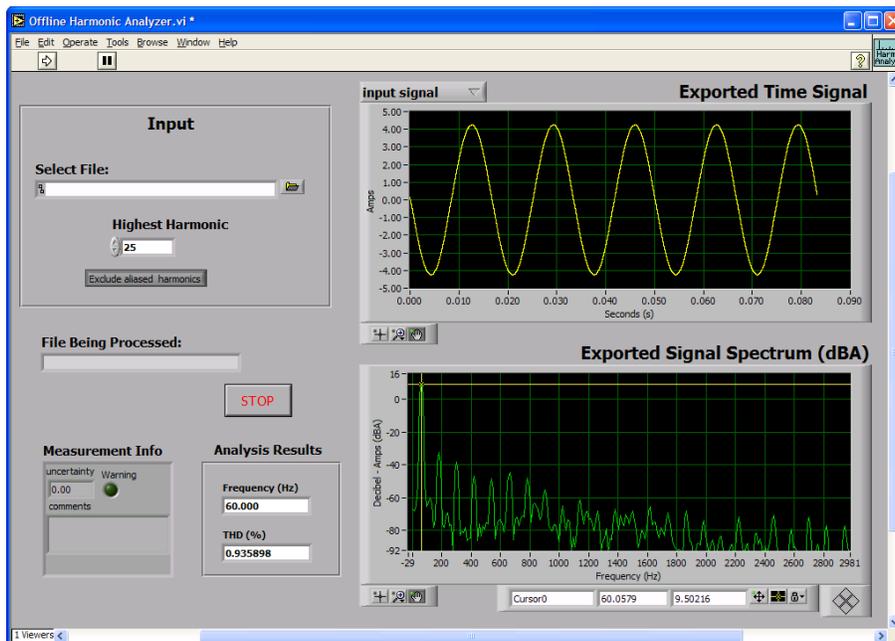


FIGURE 20. FIXTURE C HARMONICS, 2.8 amps

Nonharmonic Measurements. The emissions spectrum is shown on figure 21. A closer look at the selected sample spectrum for this fixture reveals nothing remarkable until the highest detectable frequency is reached—166.666 kHz. At that frequency, the signal strength increases to 2.3 dBm. A closer look at the frequency being measured in the time domain reveals that the sampling rate of 333.333 kHz is showing a maximum and minimum on every sample taken, meaning the actual frequency and magnitude must be measured another way. This is shown in figure 22. The Selected Sample Waveform looks triangular because each point is right on a sample, with no points in between.

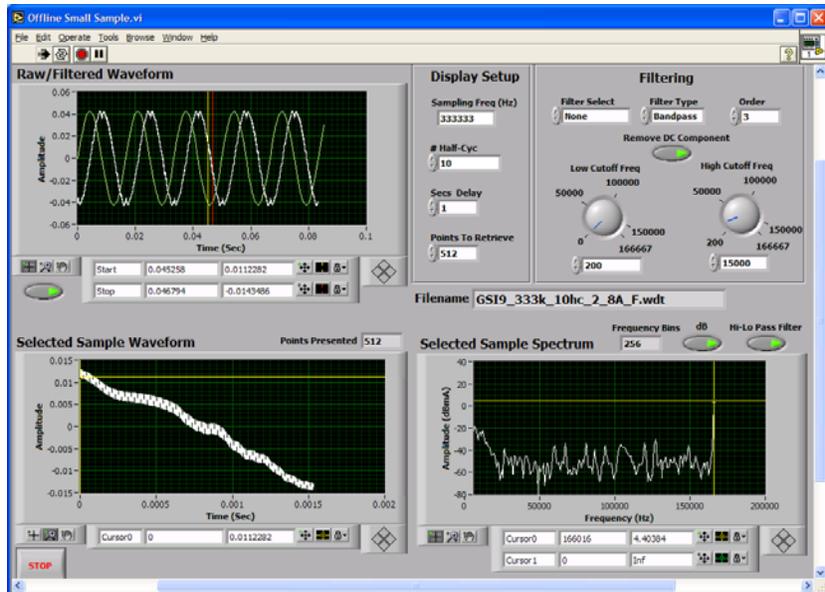


FIGURE 21. FIXTURE C SPECTRUM, 2.8 amps

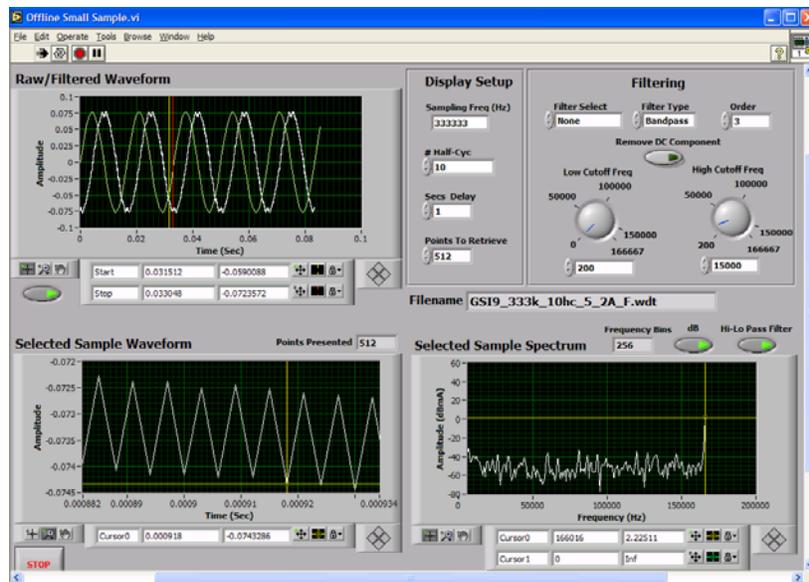


FIGURE 22. FIXTURE C SPECTRUM CLOSE VIEW

A further investigation with the Rohde and Schwarz FSH-3 Spectrum analyzer reveals that the signal is in fact about 168 kHz, just beyond the reach of the data acquisition system (see figure 23). Not only are the emissions of high frequency and at about the 2 dBm range, the presence of harmonics is visible, and they can be seen at multiples of 160 kHz, up past 1.8 MHz at -6.3 dBm. Another view reveals that these harmonics are measurable to about 5 MHz. The presence of even and odd harmonics, which are of similar strength, indicates that one is dealing with impulse radiation that occurs at the 168-kHz rate and possess a fast rise time. Figure 23 shows that the waveform in the time domain taken with a Fluke 199 in fact displays the impulse characteristic. This shows the pulses separated by about 6 microseconds, which nearly corresponds to 166.666 kHz. This does not exactly match the 168 KHz on the other view because the frequencies exhibit some jitter and will never exactly correlate.

The sample seen with the Fluke are showing about 20 mA peak-to-peak magnitude. The scaling in the legend does not include the fact that a 1:1 probe was used (see figures 23 and 24).

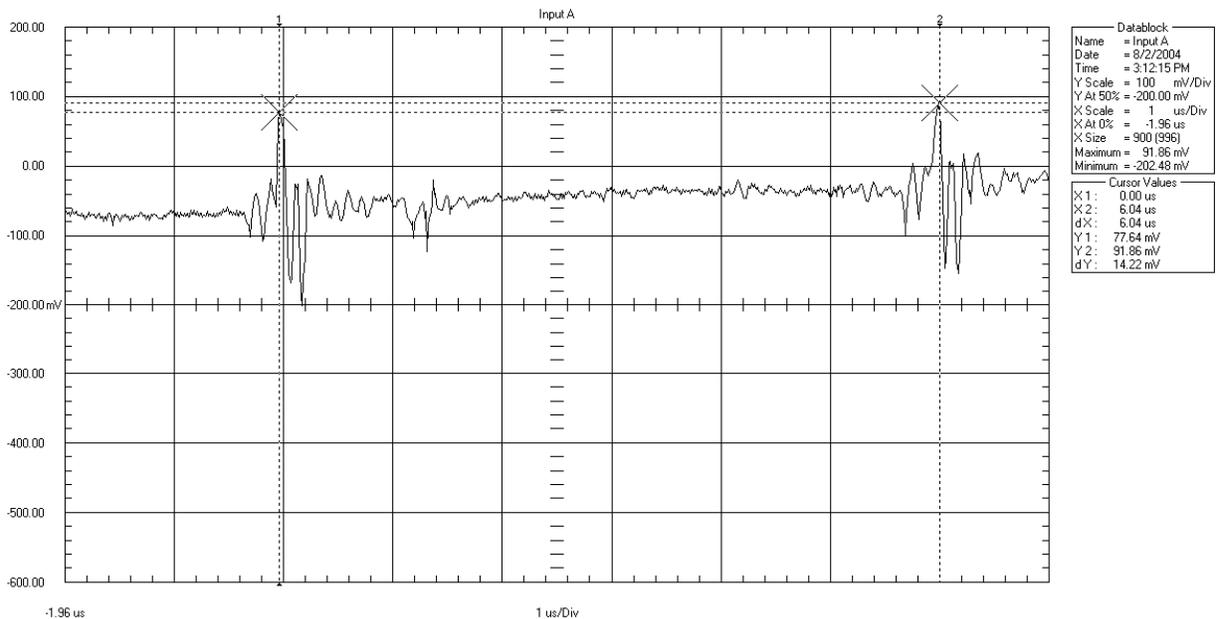


FIGURE 23. FIXTURE C EMISSION CLOSE LOOK AT THE TIME DOMAIN



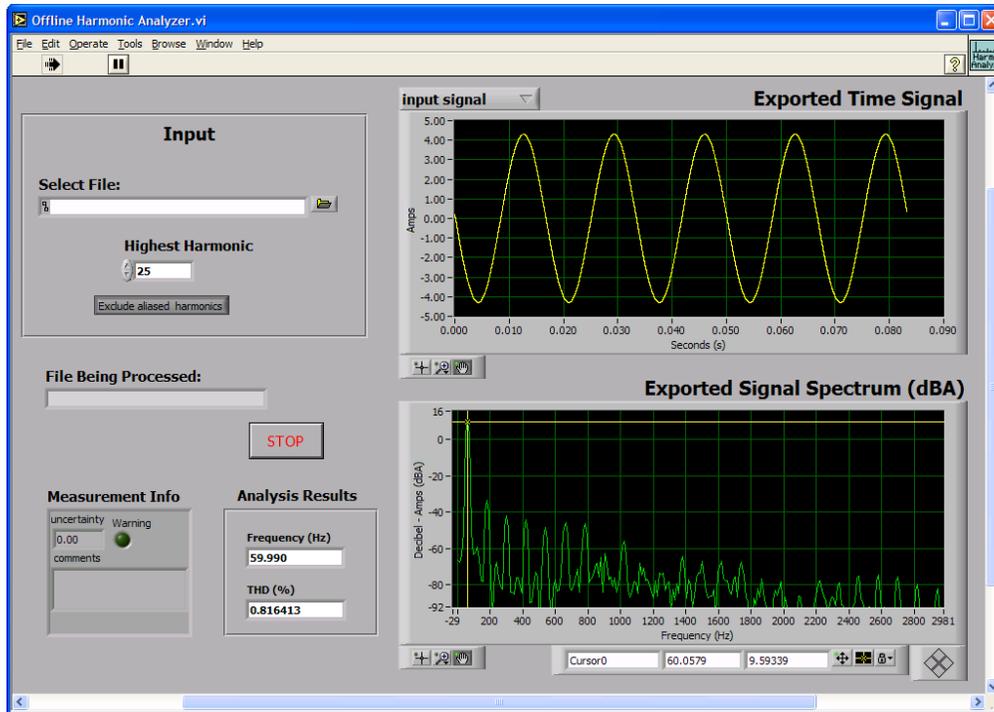


FIGURE 25. FIXTURE D HARMONICS, 2.8 amps

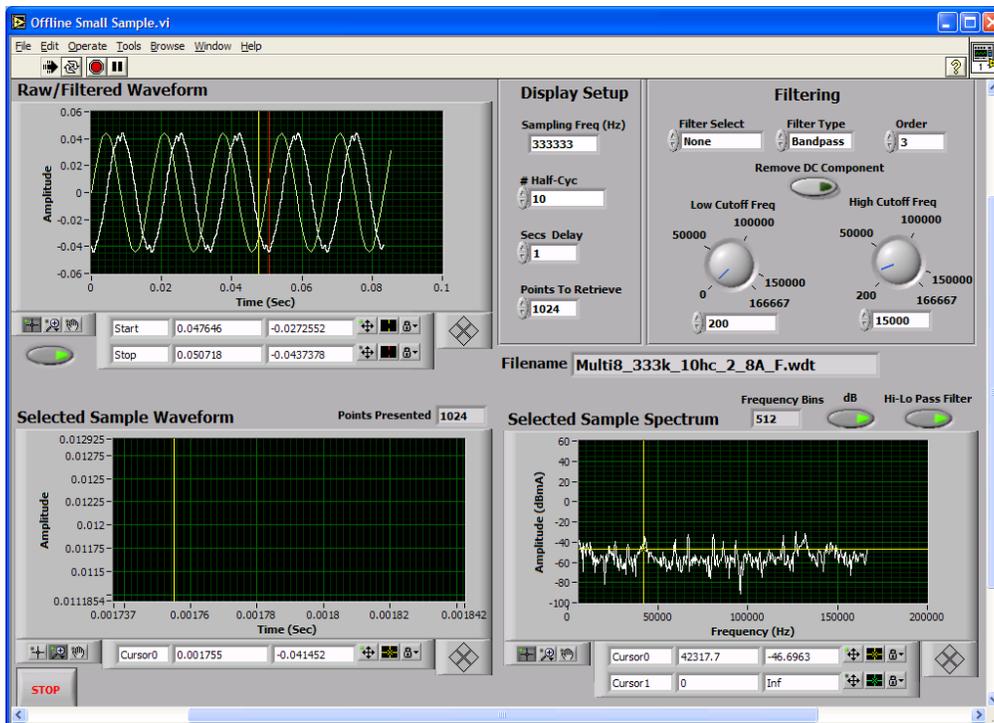


FIGURE 26. FIXTURE D SPECTRUM, 2.8 amps

FIXTURE E.

Harmonic Measurements. Refer to figure 27 for the 2.8-amp step for the harmonic measurement of this fixture. The THD is shown in figure 7e. This fixture ranged from a high of 9.8% THD at 2.8 amps to a low of 4.4% at 6.6 amps. The harmonic content is primarily lower-order odd harmonics, which achieves -70 dBA in the 3 kHz range.

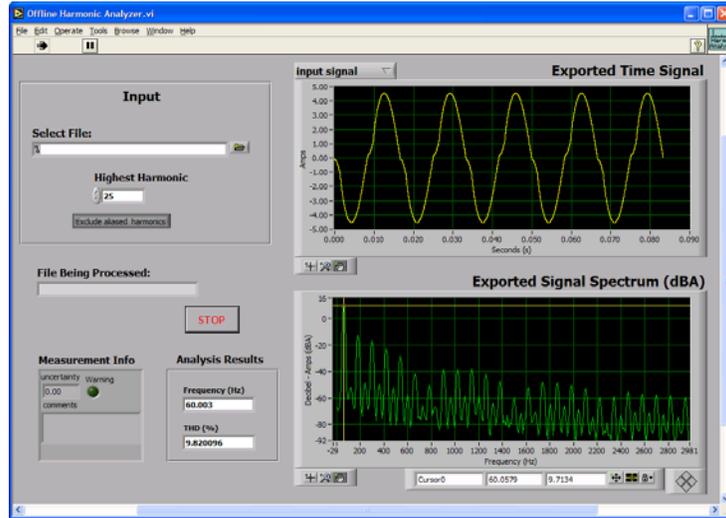


FIGURE 27. FIXTURE E HARMONICS, 2.8 amps

Nonharmonic Measurements. The emissions spectrum is shown in figure 28. This fixture showed no continuous spectral emissions. Only the noise bed is visible on the image. There is, however, a significant step in the current profile.

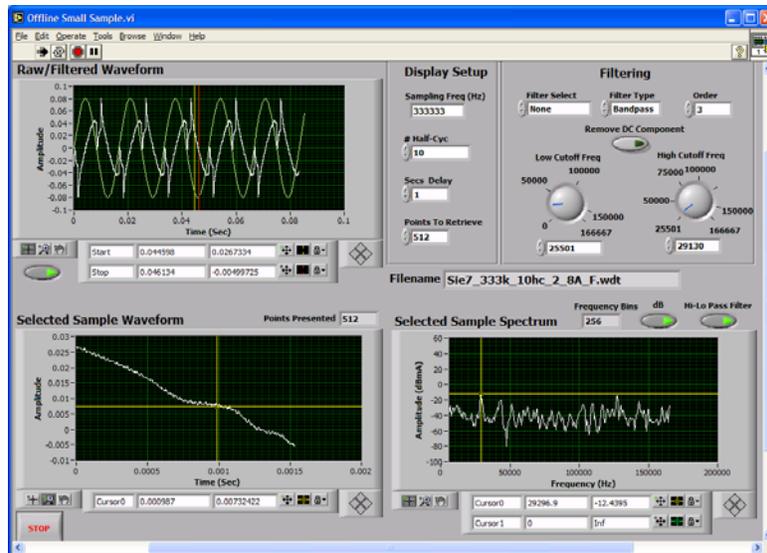


FIGURE 28. FIXTURE E SPECTRUM, 2.8 amps

Other Characteristics. Fixture E included a fast rise time step in the current of about 40 milliamps in 3 microseconds.

## DISCUSSION

The data from this study showed four out of the five LED taxiway lighting fixtures had significant harmonic emissions and nonharmonic emissions.

### FAST RISE TIME DISTORTION.

The emissions that were seen for the fixtures tested include both harmonic and nonharmonic type. The harmonic emissions are characterized by disturbances in the current, where the current diverges from a pure sinusoid. This can also be stated as the disturbances that occur on each half cycle. A look at the waveforms captured in the time domain show that samples with higher harmonic distortion contain a more pronounced discontinuity in the current. In the case of discontinuities that have a steep rise time, there is an instantaneous peak in broadband energy.

Mathematically, summing harmonically related sinusoids can generate a step in signal, or square wave. The reverse is also true; a step in the signal contains sums of harmonic sinusoids. With that said, current profiles that contain current steps have the potential of interfering with systems that operate at the frequencies that are components of those steps.

### HARMONIC EMISSIONS.

Increased harmonic distortion at low currents for some fixtures reduces the power factor of these devices, which makes them less efficient. Efficiency is generally a desirable characteristic in LED fixtures so this tends to reduce this advantage.

Harmonic distortion in the fixture, particularly when it is a result of sharp steps in the current (such as in fixtures B and E), results in sharp discontinuity of the current. The receiving circuits used by addressable lighting systems generally use some kind of bandpass filter in the front end. This step in current tends to make the bandpass filter ring at the frequency that is used for communications. These systems already contend with such a step from thyristor-fired regulators, but fixtures add a step of their own in a different portion of the ac cycle that has the potential of interfering with communications, reducing a clear area in the conduction cycle.

### NONHARMONIC EMISSIONS.

As shown in the results (the other forms of emissions that are seen in the tests), frequencies range from about 12 kHz to as much as 168 kHz. These emissions depend on the CCR step setting and which fixture is in use. Virtually all of these emissions are impulse type repeating at these high rates. They include both even and odd harmonics, which extend in some cases into the megahertz range. For this test activity, the primary issue was to make individual measurements in a quiet, controlled laboratory environment to develop an understanding of exactly what the emissions are coming from each fixture. The real issue now is the effect of hundreds of fixtures on a series circuit.

Even though the L830 transformers are in place at each fixture, the losses in these transformers is not that significant, individually. These have been measured in the order of -3 to -4 dB of loss, primary to secondary at about 150 kHz. In a situation where there is capacitive coupling of the series circuit, these losses may not attenuate the fixture emissions. It also must be considered that these emissions have the potential to be introduced in a long wire cable plant in which coupling to other cables has been seen in the field of these frequencies.

Effects of harmonic and nonharmonic emissions on addressable devices with the emissions that have been measured at the LED fixtures, it must be kept in mind that these fixtures, in some cases, could be plugged directly into an addressable device. This is not a design parameter of these units, and the introduction of a noise source locally into an addressable device is certainly something that should be investigated, as the levels measured in many cases are more than the normal signal levels under which these systems operate. The step discontinuity in the current also will cause the receive circuitry to “ring” providing another source of interference.

It is also possible that these emissions could crosstalk into proximate circuits in the same conduits. This is in many ways related to the circuit layout and routing.

#### POWER FACTOR ISSUES.

With the harmonic distortion seen, it is likely that the power factor is also reduced to the mid 80% range in some cases. This should be measured to include in-load calculation for new circuits. Most suppliers do not provide power factor numbers at lower steps, but only at the top step.

#### CAPACITIVE NATURE OF LOAD.

The power supply in some of these LED fixtures appears to have a switched capacitive front end. There have been cases where a capacitive load has caused certain CCRs to lose regulation by false triggering of the thyristors. One is aware of cases where electronic components with similar capacitive front ends caused exactly this loss of regulation, causing a mass failure of all components on a series circuit with currents in excess of 30 amps.

#### COMPATIBILITY DETECTION OF OPERATIONAL LAMP STATUS.

The input to the fixture is mostly designed as a power supply. While there is a requirement in the FAA engineering brief to provide a fail open function, the other side of the story is that these devices must be able to detect that the fixtures are operational. With an incandescent fixture, this is a simple continuity test, but with a power supply front end, the impedance characteristics are wildly variable, depending on where in the 60-Hz cycle the detection function takes place. Also, there are different methods for detection of a lamp operating, and these fixtures were not a design parameter.

## FIXTURE SETTING BRIGHTNESS BASED ON CIRCUIT CURRENT.

During the test, it was observed on several occasions that many of the fixtures provided a preset step erratically depending on the current. It has been shown that the same fixture sometimes went to a given step when the circuit current was on a nominal CCR step, and there were times that the current was within the current step tolerance stated in AC 150-5345-10E for the same step, but selected a different brightness setting. This raises the question of how all the fixtures will perform when subjected to a variety of current and circuit conditions, CCR waveforms, and transient events. The worst-case scenario is when some fixtures are at one step while others are at another step on the same circuit at the same time.

### CONCLUSION

The data from this study showed four out of the five LED taxiway lighting fixtures had significant harmonic emissions and nonharmonic emissions.

Further investigation of the LED taxiway light fixtures in a typical airfield lighting circuit is required to understand what the conducted emissions will do to the other equipment in the circuit. Areas of investigation are:

- Compatibility for communications. Develop an understanding of the impact of nonharmonic emissions has on other systems.
- Transformer test. Determine what the different transformers power consumption is for each type of fixture. Determine whether or not using a smaller transformer does actually help.
- Field measurements on a large circuit containing LED fixtures. Determine if emission levels become more of a problem as size of circuit increases.
- Fixture intensity setting performance. Determine what happens to fixtures during current changes at different intensity settings on a series circuit.
- Detection of failed lamps. Characterize the way fixtures look electrically to a control device.
- Fixture Efficiency. Determine power efficiency of various LED lighting fixtures. Compares the actual power consumption to rated power consumption.